ISSN: 0001-5113
AADRAY

ACTA ADRIAT.,
45 (2): 131-143, 2004

UDC: 551.46.06 (262-17)
Original scientific paper

# A new method for estimating climatological temperature and salinity fields in the northern Adriatic from historic data

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*The climatological fields of temperature and salinity in the northern Adriatic were determined by a new method. The fields were estimated using a large quantity of hydrographic data collected at 45 stations by the Center for Marine Research, Rudjer Bošković Institute, Rovinj, in the second half of the twentieth century, and the MEDATLAS hydrographic database. In the new method, four matrices of coefficients were extracted from the data using empirical eigen functions, Principal Component Analysis, and multiple regression. The coefficients were used to synthesize the fields. Figures showing monthly sea surface temperature and salinity in the northern Adriatic are presented. The method, with some modifications, could be used to determine climatological fields of other sea parameters (e.g., nutrients) or scientific fields (e.g., meteorology).*

**Key words:** Northern Adriatic, temperature, salinity, climatology

## INTRODUCTION

Research in the Adriatic Sea has a rich and long history stretching back over four centuries (ZAVODNIK, 1977). This long history of scientific exploration of the Adriatic Sea is occasionally the subject of review papers (BULJAN & ZORE-ARMANDA, 1976; ORLIĆ *et al.*, 1992). The northern part of the Adriatic is of special scientific interest (FRANCO *et al.*, 1982; FRANCO & MICHELATO, 1992). It is shallow (less than 50 m depth), exposed to anthropogenic influences, and has a moderate climate. A wide seasonal variability of meteorological parameters is manifested in significant seasonal variability of hydrographic characteristics (fresh water input, mainly from the Po River).

Although recent scientific investigations have focused on general circulation studies (KUZMIĆ & ORLIĆ, 1995), empirical data collection is typically sporadic and without uniform spatial and temporal resolutions (ARTEGIANI *et al.*, 1997a,b). The northern Adriatic is one of most investigated Mediterranean Sea areas. Large amounts of hydrographic data were collected during the twentieth century and stored in the MEDATLAS database. Hydrographic data was also collected by the Center for Marine Research (CMR), Rudjer Bošković Institute, Rovinj, from 45 stations in the second half of the last century.

The hydrographic characteristics of the Adriatic have been presented in many publications (BULJAN, 1953; ZORE-ARMANDA, 1963; ARTEGIANI *et al.*, 1989; ORLIĆ, 1989; SUPIĆ & ORLIĆ, 1992; CUSHMAN-ROISIN *et al.*, 2001). Recent papers focused mainly on the formation and transport of water masses (SOCAL *et al.*, 2001; VILIBIĆ & ORLIĆ, 2001, 2002; MANCA *et al.*, 2002; SUPIĆ & IVANČIĆ, 2002; VILIBIĆ, 2001). Many older hydrographic works are based on data from cruises (MOSETTI & LAVENIA, 1969; FRANCO, 1970, 1972; MALANOTTE-RIZZOLI, 1977; ARTEGIANI *et al.*, 1993; BERGAMASCO *et al.*, 1996). Some works are based on larger amounts of hydrographic data collected during longer periods (BULJAN & MARINKOVIĆ, 1956; BULJAN & ZORE-ARMANDA, 1966). Recent works are based on all available historical data. BRASSEUR *et al.* (1996) analyzed hydrographic climatology for the Mediterranean Sea and ARTEGIANI *et al.* (1997a,b) for the Adriatic Sea. These two works are based on data collected in the twentieth century and stored in the MEDATLAS database. In the current work, the same data is analyzed together with additional data collected in the second half of the twentieth century by the CMR.

The main problem was how to estimate climatological temperature and salinity fields from such a large amount of data. The method usually used is the simplest: the studied area is divided into boxes and the year into seasons; mean values are calculated for each season in each box (as in ARTEGIANI *et al.*, 1997a,b). However, if there are 12 months and small boxes, there will be few data in each box and the calculated means will be unreliable. While larger boxes and longer periods produce statistical confidence, fine spatial and temporal resolution is lost since few data are used to calculate the means. Also, the mean in one box is not independent of the means in adjacent boxes. A solution to the problem of how to maintain fine temporal (monthly means) and spatial resolutions as well as statistical confidence is found in a new method that uses empirical eigen functions, Principal Component Analysis (PCA; PREISENDORFER, 1982), and multiple regression in such a way that in each step all the data, not simply a fraction of it, is taken into account.

The method developed herein is complex and has many steps, although a simple concept lies behind its complexity. In the first step, four coefficient matrices are extracted from the data with great statistical accuracy; in the second, the estimated monthly temperature and salinity fields are reconstructed from those coefficients using empirical eigen functions.

## MATERIAL AND METHODS

The CMR database has information on station locations, depths, dates and times of measurements of temperature, salinity, density, nutrients, dissolved oxygen, and, occasionally, other parameters. This database is continuously increasing in size with new measurements. As of September 1998, there were 22662 data for temperature and salinity, measured at 132 stations, with a total of 4505 vertical profiles. On average, each vertical profile consists of 5 or 6 measurements: at the surface, at depths of 5, 10, 20, and 30 m (occasionally, 15 and 25 m), and at the bottom. Since January 13, 1921, there have been 2191 dates when measurements were taken by CMR. At station RV001 near Rovinj, probably one of the Mediterranean's most-measured stations, 1699 vertical profiles were collected by September 1998. The remaining 2806 vertical profiles were measured at 130 stations beginning in 1965. Data from 45 stations (including RV001) with more than 12 profiles were used in this study, totaling 20970 temperature and 4290 salinity profiles. The bottom data of the CMR profiles were transformed by linear transformation to the nearest multiple of 5 m. In that way only depths from 0 to 50 m in 5 m intervals from the 45 CMR stations were included in the calculations.

The MEDATLAS database contains historic hydrographic data collected mainly by classic methods (bottles) and recently by CTD probe. Only data from the northern part of the Adriatic Sea are included in this study. There were 2848 vertical profiles (bottles) and 1774 CTD profiles. MEDATLAS data were transformed to standard depths (5 m intervals). From the CTD probes, only these depths were used.

The first step was to form fictitious stations with more than 12 measurements from the MEDATLAS data. The northern Adriatic was divided into regular hexagons with 10 km long sides. For every real station, an appropriate hexagon was determined. The coordinates of the fictitious stations were calculated as the means of the real stations in the hexagon. The real stations inside the hexagons that had less than 12 measurements were redistributed to the nearest fictitious stations that had more than 12 measurements. After three iterations of this procedure, the real stations were finally distributed into 120 fictitious stations. In this way, a total of 165 stations with more than 12 temperature and salinity measurements at depths 0-50 m (in 5 m increments) were prepared (Fig. 1).

The next step was to extract coefficients for the temperature and salinity fields. In equation 1, $P(x,t)$ represents a field (temperature or salinity) measured at point $x$ and time $t$. $P_c$ is a climatological periodical field with a period of $2\pi$ (one year), $P_i$ is the inter-annual variability, and $n$ is the cumulative days in the year. We used equation 2 to estimate $P_c$ where $P_r$ is the residual deviation from the mean at position $x,y,z$. $P_s$ is periodic and can be expanded by equation 3:

$$(1)\ P(x,t) = P_C(x,\varphi(t)) + P_i(x,t),\quad \varphi = 2\pi(n-0.5)/365.24$$

$$(2)\ P_c(x,y,z,\varphi) = P_s(z,\varphi) + P_r(x,y,z,\varphi)$$

$$(3)\ P_s(z,\varphi) = a_0(z) + \sum_{k=1}^{6}(a_k(z)\cos(k\varphi) + b_k(z)\sin(k\varphi))$$

Expansion stops at the sixth harmonic since estimation of the $a$ and $b$ coefficients becomes statistically insignificant afterwards ($p>0.05$). The data were distributed among 11 depths (from 0 to 50 m in 5 m steps), so there were thousands of data for determining the coefficients with statistical certainty.

In the next step (equation 4), the coefficients were expanded as functions of depth $z$ by using LEGENDRE polynomials. LEGENDRE polynomials are advantageous because of their simple form and orothogonality on the interval (-1,1). In this way matrix A was calculated with $2\times13\times6$ alpha coefficients. With these coefficients it was possible to calculate the mean climatological temperature or salinity in the northern Adriatic

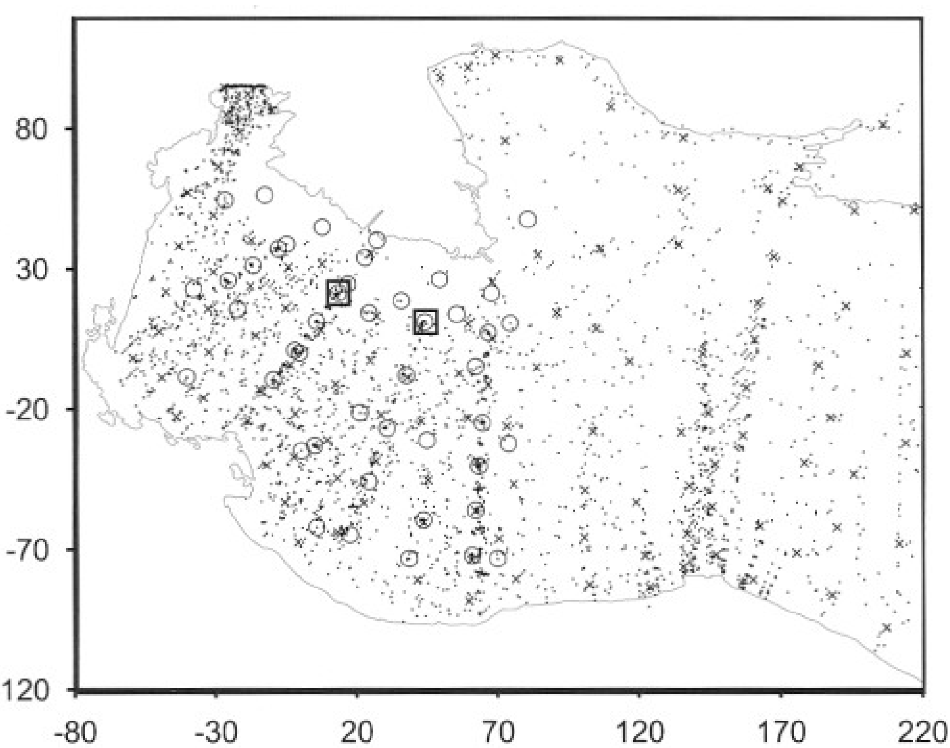


*Fig. 1. Northern Adriatic area included in the study. The origin is at 45°N, 13°E. The x coordinate is in the SE direction and the y coordinate in the NE direction, expressed in km. Dots – MEDATLAS data, crosses – fictitious stations, circles – CMR stations. Circles inside squares – stations SJ107 (left) and SJ209 (right)*

for arbitrary days in the year and at arbitrary depths from 0 to 50 m.

$$(4)\quad a_k(z) = \sum_{l=0}^{5} \alpha_{k,l} P_l\left(\frac{z}{25} - 1\right)$$

Next, table A (Fig. 2) and the calculation of $P_s(z,\varphi)$ and $P_r\ (x,y,z,\varphi)$ were determined. The $P_r$ values are mutually dependent and there was a large correlation with nearby depths, stations, and phases, so it was possible to represent $P_r$ at any station and any depth as a linear combination of some empirical eigen functions.

To determine those functions, the period $2\pi$ of phase $\varphi$ was subdivided into 14 equal parts, $r$, and for each station and depth the mean $P_r$ was determined for each of the 14 intervals. In the next step, Principal Component Analysis was used to determine that $T_r$ can be expanded with five $f_i$ functions with 80.50% variability explained. $S_r$ can be expanded with three $f_i$ functions ($f_6$ to $f_8$; 82.07% variability explained). All data were used to determine the 8 × 14 coefficients, so there is great statistical confidence that these functions represent the real spatial-temporal temperature and salinity fields in the northern Adriatic. Because each of eight $f$ functions were determined with 14 points in period $2\pi$, it was possible to expand these values as the sum of the first six harmonics (13 parameters with one degree of freedom). In this way, the $f$ function for any arbitrary day in the year could be calculated using the 8 × 13 coefficients from table B.

After determination of the eight $f$ empirical eigen functions, coefficients $a_k(p,z)$ were

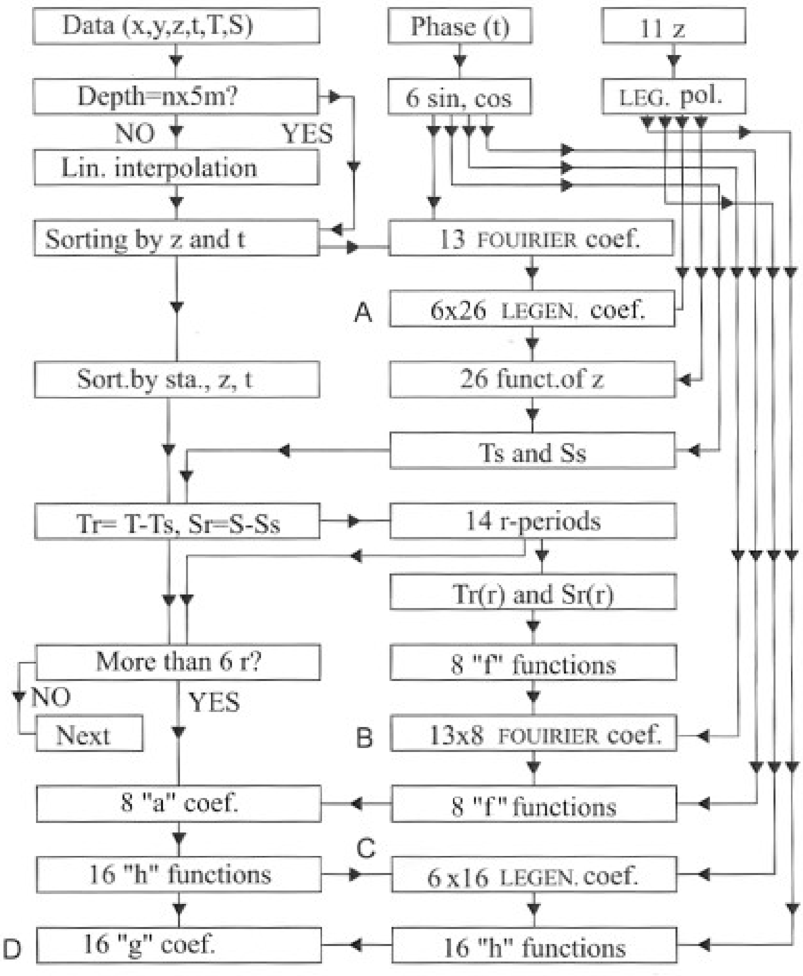


*Fig. 2. Determination of four tables of coefficients: the first part of temperature (T) and salinity (S) field determinations. Arrows indicate direction of data flow*

The northern Adriatic was covered by a grid with 10 km between adjacent net nodes. The $g$ values for every node $n$ were determined using equation 7 where $g(p)$ are values for the 165 stations. Weights $w$ are defined by equation 8 where $(x_n, y_n)$ are coordinates of nodes and $(x_p, y_p)$ are coordinates of the stations in kilometers.

$$(7)\quad g(n) = \sum_{p=1}^{165} w(n,p)\, g(p)$$

$$(8)\quad w(n,p) = \frac{\exp(-((x_n - x_p)^2 + (y_n - y_p)^2)/100)}{\sum_i \exp(-((x_n - x_i)^2 + (y_n - y_i)^2)/100)}$$

The eastern coast has many long islands that separate water masses. Therefore, the procedure to calculate $g$ at net nodes is inappropriate to this area and it is excluded in Figs. 6 and 7. In the next step, $a$ values were calculated using $h$ functions determined for every meter and $g$ functions from net nodes (equation 6). The values of the eight $f$ functions on the fifteenth day of the month were determined according to equation 5 and temperature and salinity (from a similar equation) anomalies were calculated for the grid. Finally, common temperature and salinity values for every month were calculated from table A and those values were added to $T_r$ and $S_r$ anomalies to calculate average climatological temperature and salinity fields for every month of the average year.

There was a large degree of data manipulation in determining the climatological temperature and salinity fields. Therefore, the method was tested using a simple FOURIER expansion for the first two annual harmonics of original surface data for the two neighboring stations with the largest number of measurements (stations SJ107 and SJ209). The coefficients of these expansions were compared with the coefficients of the climatological values of the stations.

## RESULTS AND DISCUSSION

There were many calculations and data manipulations in determining the climatological temperature and salinity fields in this work, so the most important step was to test and validate this method. The largest temperature and salinity variability was at the surface. Therefore, surface data for stations SJ107 and SJ209 were analyzed. A large number of measurements had been taken at these stations, making it possible to determine the constants and the first two annual harmonics coefficients with 95% upper and lower confidence level limits. These were compared with the coefficients determined by the new method (Table 1). The mean 95% confidence level range for the temperature FOURIER coefficients was 0.660°C and the mean absolute difference of coefficients determined from the original and estimated temperatures was

*Table 1. Comparison of constant and first two annual harmonic FOURIER coefficients for sea surface temperature and salinity determined from original data (Mean) with lower (95% l) and higher (95% h) 95% confidence levels compared with the same coefficients determined from values estimated by the new method (Method)*

| | | Temperature | | | | Salinity | | | |
|---|---|---|---|---|---|---|---|---|---|
| Station | Coefficient | Mean | 95% l | 95% h | Method | Mean | 95% l | 95% h | Method |
| | a0 | 16.960 | 16.776 | 17.143 | 16.758 | 36.415 | 36.181 | 36.648 | 36.280 |
| SJ107 | a1 | -5.910 | -6.163 | -5.656 | -5.957 | 1.538 | 1.216 | 1.861 | 1.320 |
| | a2 | 0.953 | 0.698 | 1.209 | 0.719 | -0.183 | -0.508 | 0.141 | -0.324 |
| | b1 | -5.243 | -5.512 | -4.974 | -4.819 | 0.348 | 0.005 | 0.690 | 0.404 |
| | b2 | 0.445 | 0.185 | 0.704 | 0.357 | 0.191 | -0.139 | 0.521 | 0.154 |
| | a0 | 17.080 | 16.752 | 17.408 | 16.805 | 37.241 | 36.920 | 37.561 | 36.977 |
| SJ209 | a1 | -5.834 | -6.313 | -5.355 | -5.997 | 0.594 | 0.125 | 1.062 | 1.087 |
| | a2 | 0.355 | -0.084 | 0.793 | 0.586 | -0.307 | -0.738 | 0.124 | -0.329 |
| | b1 | -5.200 | -5.645 | -4.755 | -4.774 | 0.565 | 0.131 | 0.999 | 0.422 |
| | b2 | 0.639 | 0.217 | 1.060 | 0.618 | -0.368 | -0.779 | 0.043 | 0.130 |

0.211°C. For salinity, the respective values were 0.724 and 0.218 psu. Therefore, we conclude that the difference is of the same range as standard errors in coefficient determinations and that the results of the method described here are realistic. While some coefficients determined by the new method were outside the 95% confidence range, some extreme values in the original data may have shifted the coefficient values. For example, the $a_1$ coefficient of the estimated salinity at station SJ209 was higher than the 95% limit (1.087 psu), while this coefficient from the original data was only 0.594 psu. The same coefficient for station SJ107 as determined from the original data was 1.538 psu and from estimated values 1.320 psu. In realistic climatological fields, it would be very unlikely that the difference in FOURIER coefficients would be as large as this. We conclude that the temperature and salinity fields estimated by the new method are realistic.

The mean climatological temperature and salinity (equations 2 and 3) were expanded in FOURIER coefficients that were functions of depth. The most important of these are the constant term and first harmonic. The constant term represents the mean annual temperature and salinity at a given depth. The first harmonic represents the approximate mean annual variability of temperature and salinity at that depth.

The mean annual temperature at the surface of the northern Adriatic is 16.6°C. The first harmonic for temperature showed a maximum of 7.6°C at the surface. With increasing depth, the constant term and first harmonic decreased. The mean temperature reached a minimum of 13.4°C at a 35-m depth, and 13.6°C at 50 m. The amplitude of the first annual harmonic decreased with depth to only 0.6°C at 50 m.

The mean annual salinity had a minimum of 35.9 psu at the surface and linearly increased to 37.3 psu at a depth of 10 m. Salinity then increased slowly and monotonously to 38.4 psu at 50 m. The amplitude of the first annual harmonic for salinity was about 1 for the first 5 m and it decreased to less than 0.1 for depths below 20 m. Thus, the annual variability of salinity in the northern Adriatic is significant only in the first 20 m.

After determining table A, the annual variability of mean temperature and salinity for the northern Adriatic was calculated (Figs. 4 and 5).

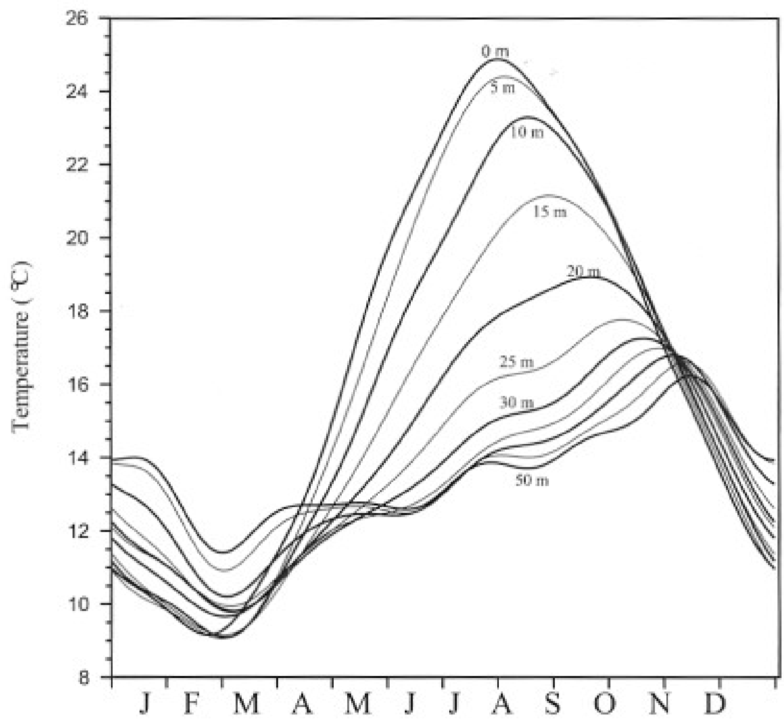


*Fig. 4. Annual mean temperature cycle in the northern Adriatic*

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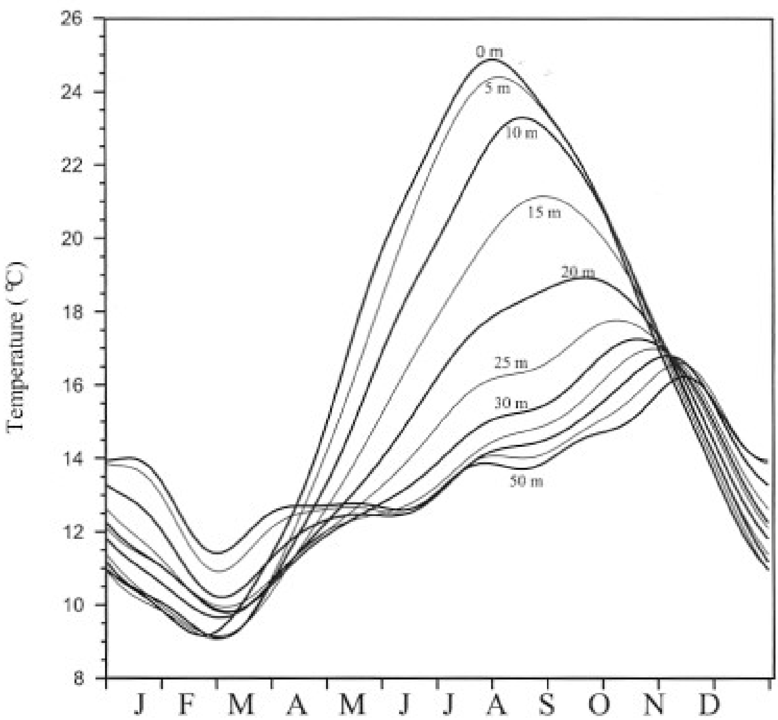


*Fig. 4. Annual mean temperature cycle in the northern Adriatic*

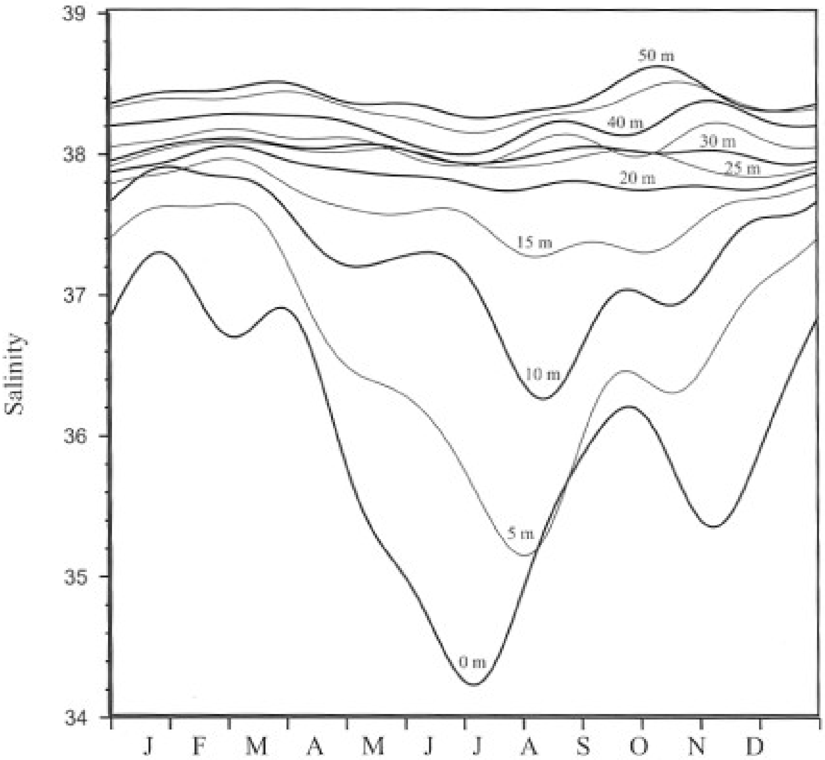


*Fig. 5. Annual mean salinity cycle in the northern Adriatic*

The mean annual salinity and temperature at the surface and depths of 5 and 10 m were determined from all the stations. Only stations with a bottom depth deeper than *h* were included in determinations at depths greater than *h*. The surface temperature at the beginning of the average year was low, reaching a minimum of about 9°C in the second half of February. The temperature increased to about 25°C by the end of July. After this, cooling began and the temperature fell to about 13°C at the end of the calendar year. At a 5-m depth, the annual temperature cycle was similar to that of the surface, although the temperature at 5 m was lower than at the surface by about 0.5°C from the end of February until September. At a 10-m depth, the temperature in the spring and summer was lower and reached a maximum of about 23°C in mid-August. At greater depths, there was a greater decrease in temperature in the spring and summer, and the maximum temperature was reached progressively later. There was a very interesting temperature inversion in late autumn and winter. The minimum temperature was reached in the second half of February at all depths.

At every position in the northern Adriatic, there were large or small deviations from the mean temperature values. The largest deviations occurred at the surface, as suggested by *h* in the empirical eigen functions (Fig. 6).

The largest contribution to the deviation was in the constant term and first harmonic. Over the course of the "mean" year, the temperature near the eastern coast was lower due to cooling by the bora wind. There was also a temperature increase in the southeast (a difference of about 6°C).

The lowest salinity was in the surface layer with a local minimum of about 36.7 psu in the beginning of March. The next absolute minimum of 34.2 psu was at the beginning of July. A third local minimum of 36.2 psu occurred at the end of September. At a 5-m depth the salinity was higher than at the surface with the exception of August. With increasing depth, salinity became higher with less annual variation. Below

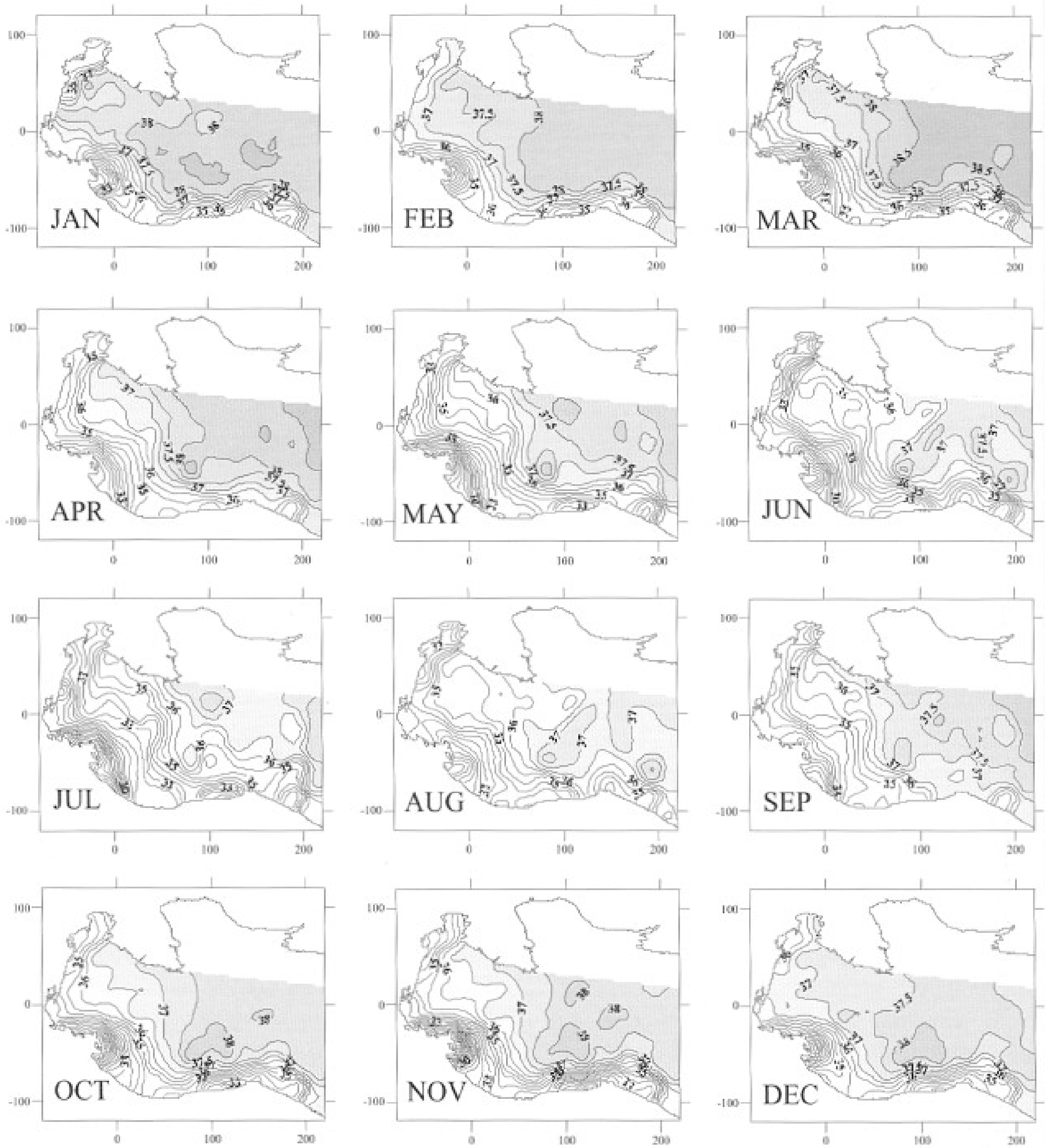


*Fig. 7. Climatology of sea surface salinity in the northern Adriatic*

20 m, salinity was near constant throughout the year and increased with depth. A maximal climatological salinity of 38.6 psu was found at 50 m in October.

The deviation of the annual salinity cycle at stations in the north Adriatic was significant only for the first 20 m (Fig. 7). Below 20 m, salinity had a quasi-homogeneous field. The only deviations occurred near the Po River delta and in the south. There, the salinity throughout the year was lower than 32 psu. In Trieste Bay, the salinity is lower due to accumulation of fresh water from rivers in northern Italy. In the south part of the northern Adriatic salinity is higher, suggesting that these waters are transported from the mid-Adriatic. In the winter, surface salinity in the northern Adriatic is higher than 38 psu with the exception of an area south of the Po River delta. In spring, the accumulation of fresh water from the Po begins east of the delta. This process continues and culminates in the summer with a minimum salinity of 33-34 psu in July. In August and September, high salinity waters from the mid-Adriatic replace low salinity waters that accumulated in the northern Adriatic during spring and summer.

These results can be compared with ARTEGIANI *et al.* (1997a,b) who defined winter as January-April, spring as May-June, summer as July-October, and autumn as November-December. They found that the temperature field in winter exhibited a marked frontal area in the northern region and along the western coast but, from our results, this is not valid for April. They found that the surface temperature in spring and summer is rather uniform throughout the northern Adriatic with cold and warm centers, although our results show that in October the surface temperature is significantly lower than in July-September. They found that strong salinity frontal areas were present in all seasons, particularly along the western coast, and that relatively fresh waters spread southeastward from spring to summer, intruding into the open sea. In our work, such spreading of fresh waters from April to September was seen. Our results are consistent with the results of ARTEGIANI *et al.* (1997a,b), although with better monthly temporal resolution.

## CONCLUSIONS

In this work we processed large amounts of temperature and salinity data from MEDATLAS and CMR by a new method. In our multistep method the climatological fields were presented as sums of common homogeneous fields $P_s(z,t)$ and deviations $P_r(x,y,z,t)$ were presented as sums of the forms $g(x,y)\ h(z)f(t)$ where the empirical eigen functions $g$, $h$, and $f$ were determined using multiple regression and Principal Component Analysis. In this way the calculated fields have very fine spatial (to the order of 10 km) and temporal (one month) resolutions. This method was validated and compared with standard procedures with the conclusion that differences are of the same range as standard errors in FOURIER coefficient determinations. In other words, the results of the method described in this paper are realistic.

The surface temperature had a minimum (9°C) in February and maximum (25°C) in July. The lowest salinity was in the surface layer. There was a local salinity minimum (36.7 psu) in March, an absolute minimum (34.2 psu) in July, and a third local minimum (36.2 psu) in September. The temperature decreased with depth while the salinity increased. Annual amplitudes and deviations at particular stations from horizontally averaged means decreased with depth for temperature and salinity. The method of data decomposition to the empirical eigen functions described here enabled estimation of the climatological temperature and salinity fields in the northern Adriatic. There was a temperature increase in the southeast direction and high salinity frontal areas along the western coast throughout the climatological year. From April to September, relatively fresh waters spread southeastward, intruding into the open sea in the northern part. These results are consistent with earlier results but have better spatial and temporal resolution.

It is possible to use the method described herein with some modifications to determine the climatological fields of other parameters in the sea, for example nutrients, or other scientific fields, for example meteorology.

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Received: 13 May 2003
Accepted: 27 September 2004

# Nova metoda procjene klimatoloških polja temperature i saliniteta u sjevernom Jadranu na temelju povijesnih podataka

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## SAŽETAK

Prikazana su klimatološka polja temperature i saliniteta u sjevernom Jadranu, određena na temelju velikog broja hidrografskih podataka prikupljenih od strane Centra za istraživanje mora (CMR) Instituta "Ruđer Bošković" u Rovinju u drugoj polovici dvadesetog stoljeća na 45 postaja, zajedno s drugim podacima prikupljanim u dvadesetom stoljeću u ovom području (baza podataka MEDATLAS). Polja su određena novom metodom. U ovoj metodi su u prvom koraku određene 4 tabele koeficijenata iz svih podataka korištenjem empirijskih svojstvenih funkcija, metode glavnih komponenata i višestruke linearne regresije. U drugom koraku iz ovih koeficijenata određena su klimatološka polja.

**Ključne riječi:** sjeverni Jadran, temperatura, salinitet, klimatologija